PERFORMANCE REPORT

NEURAL NETWORKS FOR REAL-TIME SENSORY DATA PROCESSING AND SENSORIMOTOR CONTROL

Grant N00014-90-J-1545

Period of Performance: 3 Years

Starting Date: January 1, 1990

Tuesday, June 18, 1991

Randall D. Beer
Principle Investigator
Departments of Computer Engineering
and Science, and Biology
Case Western Reserve University
Telephone: (216) 368-2816

1. Experimental Work

Our experimental work over the past six months has focused upon two distinct areas. First, we have continued our work on behavioral analysis of the turn. Second, we have completed our physiological study of the current-frequency properties of the ventral giant interneurons (vGIs) and moved on to a study of the relative temporal properties of the various vGIs as they respond to wind from various directions.

Having documented the basic leg movements in the meso- and metathoracic (T2 and T3) legs that are associated with turns away from various different angles, we have moved on to questions regarding plasticity of the turning parameters. Since the T2 legs provide much of the rotational movement during the turn, amputation of both T2 legs has a profound effect on the animal's ability to turn. Immediately after surgery, the animal still escapes, but does not turn as well as normal animals. Yet when the animal's are retested two days later, they have altered their turning movements to compensate for the loss of T2 legs and are now capable of turning as well as normal animals. The plasticity that is involved in this rearrangement can be the object of future quantitative modeling projects similar to those which have been performed relative to cercal ablation in the last year.

We have also made an observation regarding the prothoracic (T1) legs that will require follow-up in conjunction with modeling efforts. The legs of the T1 segment utilize movement at the joint between the thorax and the coxa to a much greater extent than do the legs of the T2 and T3 segments. This is a very complex joint which actually has the freedom of motion approaching that of a ball and socket joint. As a result of this movement, analysis of video records relying heavily upon a ventral view of the leg joints has proved problematical for the T1 legs. Indeed, we feel that a real analysis of the movements involved with the T1 legs will require accurate video images in multiple planes coupled with three dimensional reconstruction. This will best be analyzed in conjunction with a modeling effort which is planned to simulate the real three dimensional movement of each leg. Since the T1 leg appears to provide some of the rotational movement during the turn, this will be an important aspect of our future studies.

In physiological investigations, a graduate student, Songhai Chai, has completed analysis of the current-frequency relationships of the vGIs. In this work individual vGIs were impaled with microelectrodes. Current was injected into the interneuron through the microelectrode, using the bridge circuitry of our DC amplifiers. We could then measure the number of action potentials generated by varying levels of injected current. At the end of the experiment Lucifer Yellow dye was injected into the cell for subsequent identification on morphological grounds. With these experiments, we have been able to generate current-frequency curves for each of

the large vGIs (1-3). The shapes of these curves are similar for each vGI. Curves for some smaller interneurons are also similar in shape but the threshold is somewhat shifted downward, indicating a relationship between size and threshold that might be predicted by increased input resistance. The curves have also been related to previously published records on firing frequency relative to wind direction. All of these data can now be used to make the computer model more physiologically accurate.

Having completed this study, we have now moved on to investigate the relative timing of the various vGIs within wind responses from various different directions. In order to model the transfer of information from vGIs to thoracic interneurons, we must not only know which vGIs connect to each thoracic interneuron but also when the vGI activity activates those cells. The relative timing of vGI action potentials within wind puffs could change in a systematic fashion along with wind angle. Relative latency could then contribute to the directional properties of the system. To measure temporal relationships, Songhai Chai has begun to record from vGIs intracellularly in pairs. Once two vGIs are impaled standard wind puffs can be presented to the animal from various different directions. The relative latency of the two vGIs can then be determined for wind from different directions and plotted on polar graphs. Preliminary findings indicate that differences in wind direction are indeed enhanced by latency. For example, the two GI1s have a left-right bias. That is left GI1 fires much stronger to wind from the left than to wind from the right. Our data indicates that this effect may be enhanced by the fact that the right GI1 is not only firing fewer action potentials, but that those action potentials are actually arriving much later than the left GI1 action potentials. As a result they may not contribute much to the initial response in the postsynaptic thoracic interneurons.

2. Modeling and Simulation

We have continued to improve our models of the ventral giant interneurons by incorporating additional constraints. Since the vGI firing curve experiments were completed, we have fit sigmoids to the actual firing curves. Our current vGI models now incorporate the following information: (1) the known signs and connectivity from the cercal hairs; (2) the experimentally determined average firing curves for each of the vGIs; (3) the normal wind-responses of each vGI; (4) the wind responses of each of the vGIs following ipsilateral cercal ablation. We are currently applying this model to an examination of the possible sites and mechanisms of the plasticity underlying adaptation to cercal ablation.

Two new projects have just begun. In the first, we are constructing a Getting-type current clamp model of the temporal firing properties of the vGIs. One of the interesting results of the recently completed vGI firing curve experiments was that the change in firing frequency over time that was observed in response to current injection was similar to that seen in response to

puffs of wind. Our current vGI models ignore this temporal aspect of the vGIs' activity. By extending our vGI models to incorporate the actual time of occurrence of individual action potentials, we hope to account for these data. A temporal model of the vGIs is an important intermediate step toward acheiving an understanding the computations performed by the next stage in the escape circuit, the thoracic interneurons.

In the second new project, we have begun to incorporate physical dynamics into the kinematic model of the cockroach's body that we previously employed. The dynamic body model we are constructing will be flexible enough to allow segments and joints to be easily changed as the model evolves. In addition, the new body model will have a more sophisticated user interface than our original model, which will make it a useful aid for understanding the three dimensional motion of the actual legs from high speed video camera data. When muscle models are added to this dynamic body model, we will be able to begin to relate muscle EMGs to leg movements as well as model the forces applied during the turn.

The goals of this grant are twofold: to develop a biologically accurate computer model of the cockroach escape response and to explore the application of biological control ideas to the construction of more robust and flexible autonomous robots. We have begun new work related to the second goal which is aimed at automatically constructing adaptive neural network controllers for a given body and environment. Specifically, we have used genetic algorithms to evolve continuous-time recurrent neural network controllers for chemotaxis and locomotion. In the locomotion experiment, we used the two dimensional insect model which we have employed in previous work. The performance measure to be optimized was simply the forward distance traveled by the insect in a fixed amount of time. Because the simulated insect can only make forward progress when it is statically stable, the genetic algorithm had to evolve a neural network which not only generates the appropriate rhythmic control signals for each leg, but also coordinates the individual leg movements in such a way that the insect is continuously supported. The genetic algorithm evolved a number of neural controllers which produced the tripod gait, in which the front and back legs on each side of the body move in phase with the middle leg on the opposite side. This is the gait which is typically observed in fast walking insects.

Insects which were given access to a sensory signal encoding leg angle always evolved controllers which were completely dependent upon this signal; if the sensors were later removed the insect was unable to rhythmically lift its legs. If no such sensory signal was provided, oscillatory controllers evolved which were capable of intrinsically producing the appropriate rhythmic motor outputs. By using a composite fitness function obtained by averaging an insect's performance both with and without sensors, we were able to evolve controllers which took advantage of sensory feedback to fine-tune leg movements if it was

available, but could operate in its absence if necessary. We believe that this may be a fruitful approach to automatically constructing adaptive neural controllers for a given body and environment, and deserving of further exploration.

3. Robotics

The construction of the physical robot and its interface electronics is finished. The wiring of the two motors and two potentiometers has been completed for all six legs. In addition, twelve proportional feedback position controllers with deadbands have been built using analog components. The output of the motor neurons in each leg controller network is a velocity, which is then integrated to obtain a desired position. Each position controller drives its corresponding motor with a voltage proportional to the difference between the desired position and the actual position of that joint. This approach lends a muscle-like property to the legs.

The robot is currently walking under the control of the locomotion neural network. The neural network is simulated in C on a PC which interacts with the position controllers through D/A and A/D boards. We have found that the robot can be made to walk at a variety of different speeds simply by varying the level of activity of the command neuron in the locomotion controller. At low speeds of walking, distinct metachronal waves can be observed on each side of the body. At higher speeds, the robot exhibits the tripod gait. Thus the range of gaits is quite similar to those we observed in our previous simulations of the locomotion controller.

However, there are some differences in cross-body phasing between the robot and our earlier simulations. It appears that these may be due to asymmetric temporal lags in the physical robot which did not exist in the simulated body. We are currently testing this hypothesis and fine-tuning the robot to minimize these lags. We are also performing some lesion studies in order to compare the robustness of the physically embodied locomotion controller with its robustness in simulation.

Publications

Beer, R.D., Kacmarcik, G.J., Ritzmann, R.E. and Chiel, H.J. (in press). A Model of Distributed Sensorimotor Control in the Cockroach Escape Turn, to appear in R.P. Lippman, J. Moody and D.S. Touretzky (eds.) *Advances in Neural Information Processing Systems 3*. Morgan Kaufmann Publishers.

Beer, R.D., Kacmarcik, G.J., Chai, S., Ritzmann, R. and Chiel, H.J. (1991). Ventral Giant Interneuron Wind Fields in the Cockroach Modeled with Constrained Backpropagation, *Society for Neuroscience Abstracts* 17.

Beer, R.D. and Gallagher, J.C. Evolving Continuous-Time Recurrent Neural Networks for Adaptive Agent Control. Submitted to the 1991 IEEE Conference on Neural Information Processing Systems.

Gallagher, J.C. (1991). Genetically Directed Design: An Experiment in Adaptive Locomotion Control. M.S. Thesis, Dept. of Computer Engineering and Science, Case Western Reserve University.

Kacmarcik, G.J. (1991). A Neuroethological Model of the Cockroach Escape Turn. M.S. Thesis, Dept. of Computer Engineering and Science, Case Western Reserve University.

Larsson, P. (1991). Electronic Hardware of Milquetoast the Walking Robot. M.S. Project, Dept. of Electrical Engineering and Applied Physics, Case Western Reserve University.

Ritzmann, R.E., Pollack, A.J., Hudson, S. and Hyvonen, A. (1991). Convergence of multimodal sensory signals at thoracic interneurons of the escape system of the cockroach, *Periplaneta americana*. *Brain Research* (in press).

In Preparation

"Reconstruction of Ventral Giant Interneuron Windfields in the Cockroach Using Constrained Backpropagation," by Randall D. Beer, Gary J. Kacmarcik, Songhai Chai, Roy E. Ritzmann, and Hillel J. Chiel.

"A Distributed Neural Network Architecture for Hexapod Robot Locomotion," by Randall D. Beer, Hillel J. Chiel, Roger D. Quinn, Ken Espenschied and Patrik Larsson.

"Motion Analysis of Leg Joint Angles during Wind-Evoked Escape Turns of the Cockroach, *Periplaneta americana*," by Scott W. Nye and Roy E. Ritzmann.